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FIRE PROTECTION OF LARGE AIR FORCE HANGARS

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Final Report

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This report describes a study related to the fire protection of large aircraft hangars. The study directly develops and augments a previous effort completed for the Air Force Weapons Laboratory in April 1974. This report discusses the attenuation of Aqueous Film-Forming Foam (AFFF) in an environment of elevated temperature, foam particle fire plume penetration, supplementary low-level foam systems, floor drainage systems and draft curtains. In addition, 900-sq ft JP-4 fire test results are discussed. The tests were the major effort
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of the program and were intended to evaluate the general effectiveness of 3 percent and 6 percent AFFF when discharged singly and jointly from overhead and ground level. The results of the study discussed in this report indicate that FC-203 is an extremely effective deluge system agent when applied at design densities of 0.16 gpm/ft² but dramatically loses effectiveness when applied at a rate of 0.125 gpm/ft²; at an application rate of 0.1 gm/ft² an oscillating monitor nozzle is capable of achieving 90 percent fire control in 30 to 45 sec under optimum conditions, a performance capable of aircraft protection; and the potential for large reduction in water demand with no sacrifice to fire fighting effectiveness exists with closed heat AFFF sprinkler systems in hangars, as contrasted with AFFF deluge systems.

sq ft

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SECTION I
INTRODUCTION

In the last two decades, since the development of foam water sprinklers, much has changed with respect to the protection of aircraft hangars and their contents. Necessarily, with the advent of substantially larger aircraft came the development of larger and more complex hangars. The associated hazards as well as their magnitude grew proportionally. As a result, new and better ways to cope with the problem were investigated. New fire fighting agents and concepts were developed as well as new detection and hardware packages. Correspondingly, a great deal of research, testing and evaluation was undertaken. Since the technological development of aircraft hangar protection has been and continues to be a dynamic process, it has been almost impossible to answer all the questions which exist at any given time. In addition, the recent national awareness of and concern, for environmental preservation have further raised the issue of the possibility of inland waterway pollution by fire fighting agents. The intent of the present study was to address a number of the unanswered issues.

SECTION II
OBJECTIVES

The objectives of this study of Fire Protection for Large Air Force hangars can be stated broadly as follows:

1) Conduct large-scale fire tests aimed at

a) determining further the effectiveness of 3-percent aqueous film forming foam (AFFF);

b) determining the effectiveness of AFFF systems at high ceiling level versus ground level systems and a combination of both in suppressing large fuel spill fires.

2) Measure the attenuation of foam in a fire environment.

3) Investigate the effective size distribution of AFFF particles that can penetrate a given fire plume.

4) Investigate the feasibility of using supplementary low level foam systems, other than oscillating monitor nozzles, to provide complete floor coverage under aircraft areas.

5) Determine the merit of injecting non-pollutant fire retardants including alternative low expansion foams.

6) Research and evaluate the effectiveness of floor drainage and draft curtains.

SECTION III
AFFF EFFECTIVENESS

3.1 GENERAL

This portion of the research effort involved large-scale fire test activity. It was the intent of this activity to address two general areas of investigation of AFFF effectiveness:

1) A continued evaluation of 3-percent AFFF

2) An evaluation of the effectiveness of AFFF systems at high ceiling level versus ground level foam systems or a combination of these systems to suppress large fuel spill fires.

The two 3-percent AFFF's evaluated previously under contract F29601-73-C-0043 were to be used in this continued investigation. However, just prior to commencement of test activities, it was announced by one manufacturer that their 3-percent agent currently being produced was no longer recommended for application with conventional sprinkler heads. Consequently, tests were conducted using only one 3-percent AFFF, FC-203*.

In recent years, strong support has evolved, largely on the basis of conjecture, for the use of closed-head, ceiling AFFF sprinkler systems. Just prior to the start of this work effort, Factory Mutual Research (FMRC) conducted a series of laboratory fire tests** in which the AFFF suppressant was discharged through a closed head sprinkler. This work supports the potential of substantial cost savings associated with system installation. In addition to the basic question of effectiveness, other issues are: optimum sprinkler temperature rating, storage of AFFF in sprinkler pipes, design density and area of demand. FMRC believes the closed-head AFFF system potential to be great for small hangars and large hangars equipped also with supplementary ground level foam systems. This concept falls completely within the scope of the second major area of investigation. Consequently, several tests were conducted to determine the feasibility of such an approach to hangar protection.

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* Product of the 3M Company
** FMRC Report Serial No. 22352, January 1975

As will be evident, the test data and conclusions from any given test quite often relate to both major areas of investigation.

3.2 LARGE-SCALE TESTS

3.2.1 Test Plan

During the previous study, exceptionally good test results were recorded using FC-203 (3.4 percent) in a deluge system at a design density of 0.16 gal/min/ft^2. As part of the agent's further evaluation, a test was planned for which the design density would be reduced to 0.125 gal/min/ft^2 while other parameters would be held constant. An identical test using FC-200 (6.2 percent) was also planned in order to provide a direct comparison of the agents; two tests were conducted employing a monitor nozzle (0.1 gal/min/ft^2) with no overhead protection. In addition to further evaluating FC-203 and comparing its fire suppression capability to FC-200, these tests also address the second of the general areas of AFFF effectiveness mentioned in Section 3.1.

A test was also planned to evaluate the effectiveness of the combination of an AFFF deluge system and a monitor nozzle. From much previous test activityit was known that as long as the horizontal reach and flow characteristics of the monitor nozzle were not impeded by obstructions, the nozzle should be the dominant force in the suppression of the fire. Control and extinguishment times should, for all practical purposes, be identical to those of a monitor nozzle alone. Since such a test was judged to be meaningless, the concept of a closed head AFFF sprinkler system for hangar protection would be evaluated. An FC-203 test was, therefore, planned in which a monitor nozzle (0.1 gpm/ft^2) would be used in conjunction with a closed head sprinkler system (0.16 gal/min/ft^2).

To permit a realistic evaluation of the closed head concept, a test employing a closed head sprinkler system alone could not be avoided. Such a test would, in addition, provide a direct comparison with the previous test and, thus, further illuminate the issue of monitor nozzle capability.

Because of the specifics of the test setup, discussed in Section 3.2.3, tests were not be conducted in the order in which they were planned. In order to conserve agent, all tests utilizing FC-203 were run prior to any tests using FC-200.

3.2.2 Test Procedure

A 30 ft x 30 ft (900 sq ft) diked pool of JP-4 provided the fuel source for all fire tests (Figure 1); 140 gal of JP-4 were allowed to flow for a 2-min period through an eight-nozzle arrangement into the diked area prior to ignition by electric matches. All tests were unobstructed.

After ignition, fuel continued to flow at the rate of 70 gpm until suppression or intentional shutdown. Wherever employed, the deluge system and/or the monitor nozzle were activated immediately following the actuation of the second of three 140°F Fenwal rate-compensated heat detectors located at the ceiling, 60 ft above the fuel surface. These detectors were 20 ft east, north and south of the geometric center of the fire. The sprinklers in the closed head system operated when the fusible links attained the proper temperature.

Since the dike was constructed of polyethylene it melted completely soon after ignition, allowing for the flow of foam into the fire area from beyond the fire area boundary. From previous experience it was known that the fire area would not enlarge due to the melting of the dike. It was also known that all of the fuel could not be consumed during the expected test duration.

Agent was proportioned into the water system from a 550-gal bladder tank proportioner (Figure 2) calibrated for each agent. This balance pressure proportioner uses a venturi type controller which is capable of accurately compensating for changes in total flow over a wide range. Agent was proportioned into a riser at ground level, 60 ft beneath the ceiling. Several feet downstream of the proportioner, a tap was installed from which periodic samples were taken in order to check agent concentration. The monitor nozzle, whenever used, was fed from a manifold through two hose lines from the same system.

Figure 1 900 Sq-Ft Diked Pool

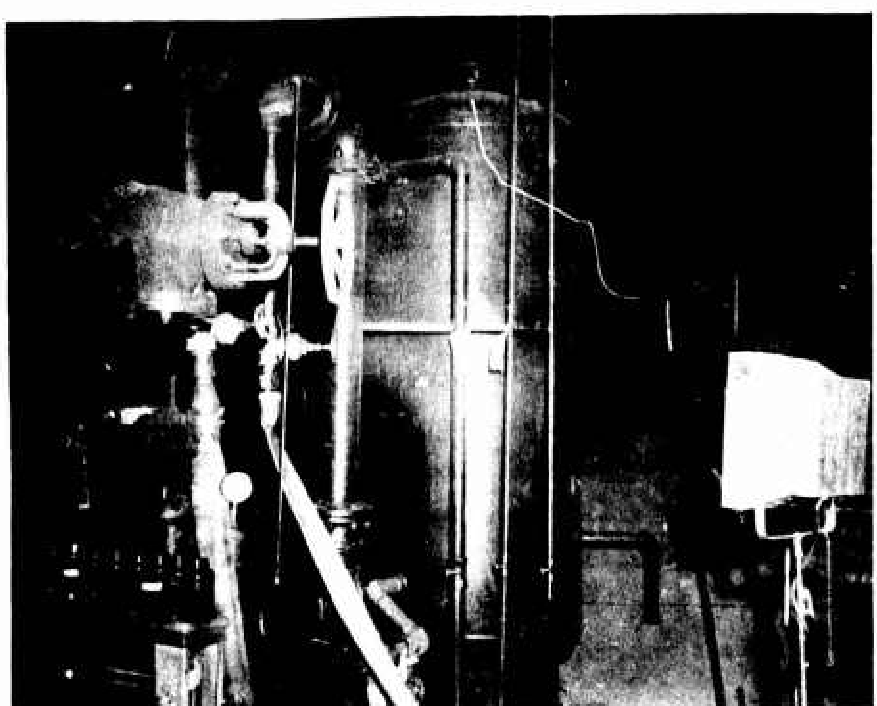

Figure 2 550-Gallon Bladder-Type Proportioner

For all tests, the appropriate system(s) was primed to the point of actuation with foam solution: 1) to the cross main for the deluge system; 2) to the sprinklers in the closed head system; and 3) to the nozzle whenever the monitor was employed.

The monitor nozzle used was a Feecon Corporation Model OM-500, calibrated to provide an average density of 0.1 gpm/ft^2 over the fire area at a discharge pressure of 80 psi. This was accomplished with an 8-sec cycle time over a 50° arc at an elevation angle of 15°. The nozzle was located 85 ft north of the center of the fire.

The deluge system consisted of 48 Grinnell standard style upright sprinklers arranged on a 130-sq-ft spacing. The protected area greatly exceeded the fire boundaries, covering approximately seven times the fuel area (Figure 3).

The closed head sprinkler system consisted of 86 Grimes Model D sprinklers (Figure 4). 360°F rated fusible links were used in all tests employing the closed head system. Except for peripheral sprinklers, spacing was 130 ft^2, allowing for floor area coverage of approximately 11,000 ft^2.

During each test, whenever possible, system actuation time, time of first water flow at sprinkler, time of visible foam flow at sprinklers, 75 percent and 90 percent control times, extinguishment time, solution flow rate, agent concentration (by refractometer), expansion ratio, drainage rate time, and anomalies, were recorded.

3.2.3 Test Results

During the first test (.125 gpm/ft^2, FC-203) 48 closed head building sprinklers in addition to those of the deluge system were inadvertently actuated. Since total flow was held constant, the result was a 0.125 gpm/ft^2 initial design density which decays to approximately 0.06 gpm/ft^2. The test was, therefore, repeated as planned as Test No. 2.

In Test No. 5 (closed head, FC-203), foam concentrate supply was accidently exhausted less than 30 sec into the test, reducing the overhead protection to a closed head water sprinkler system. This test was repeated

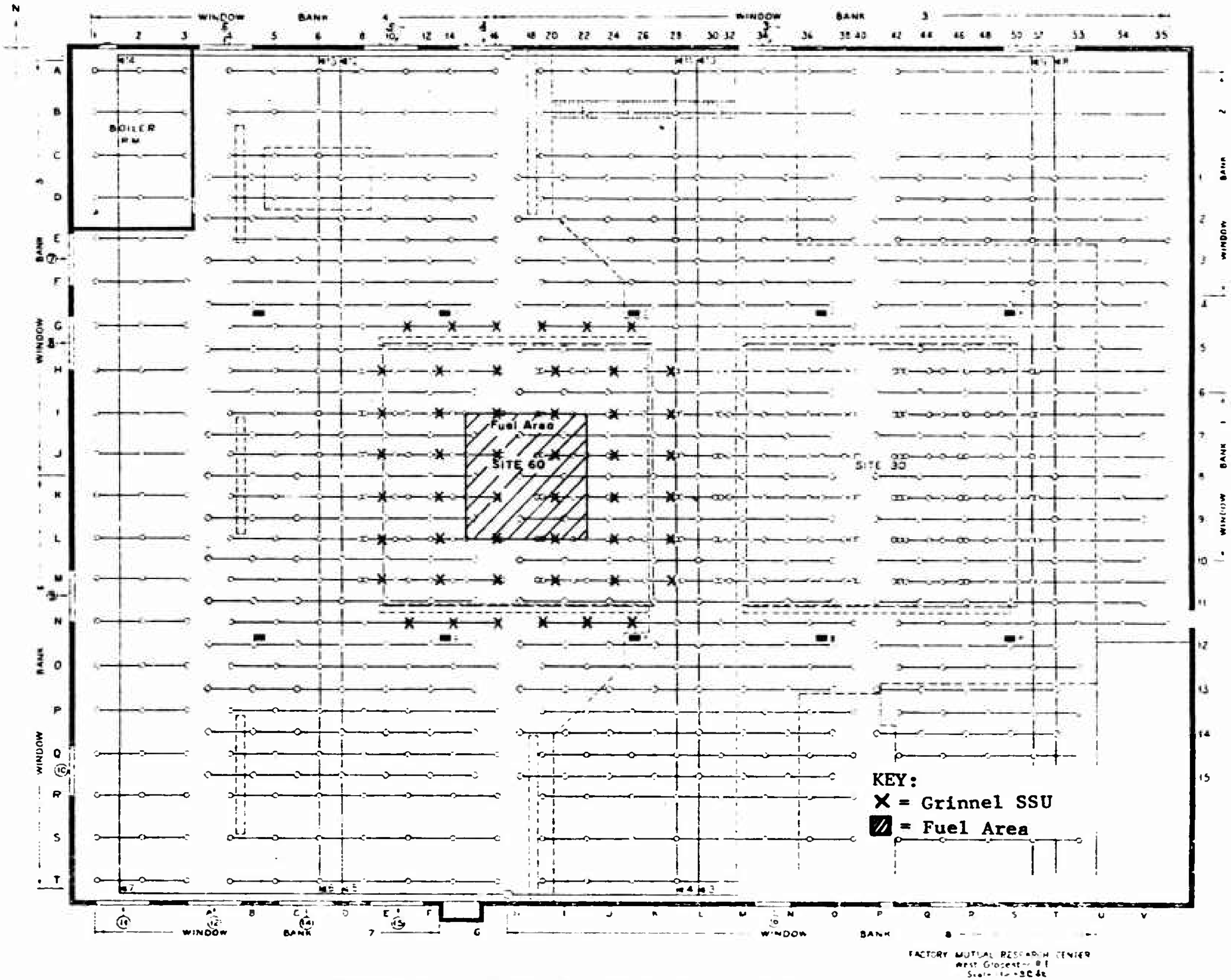

Figure 3. 130 Sq. Ft. 48-Head Deluge System

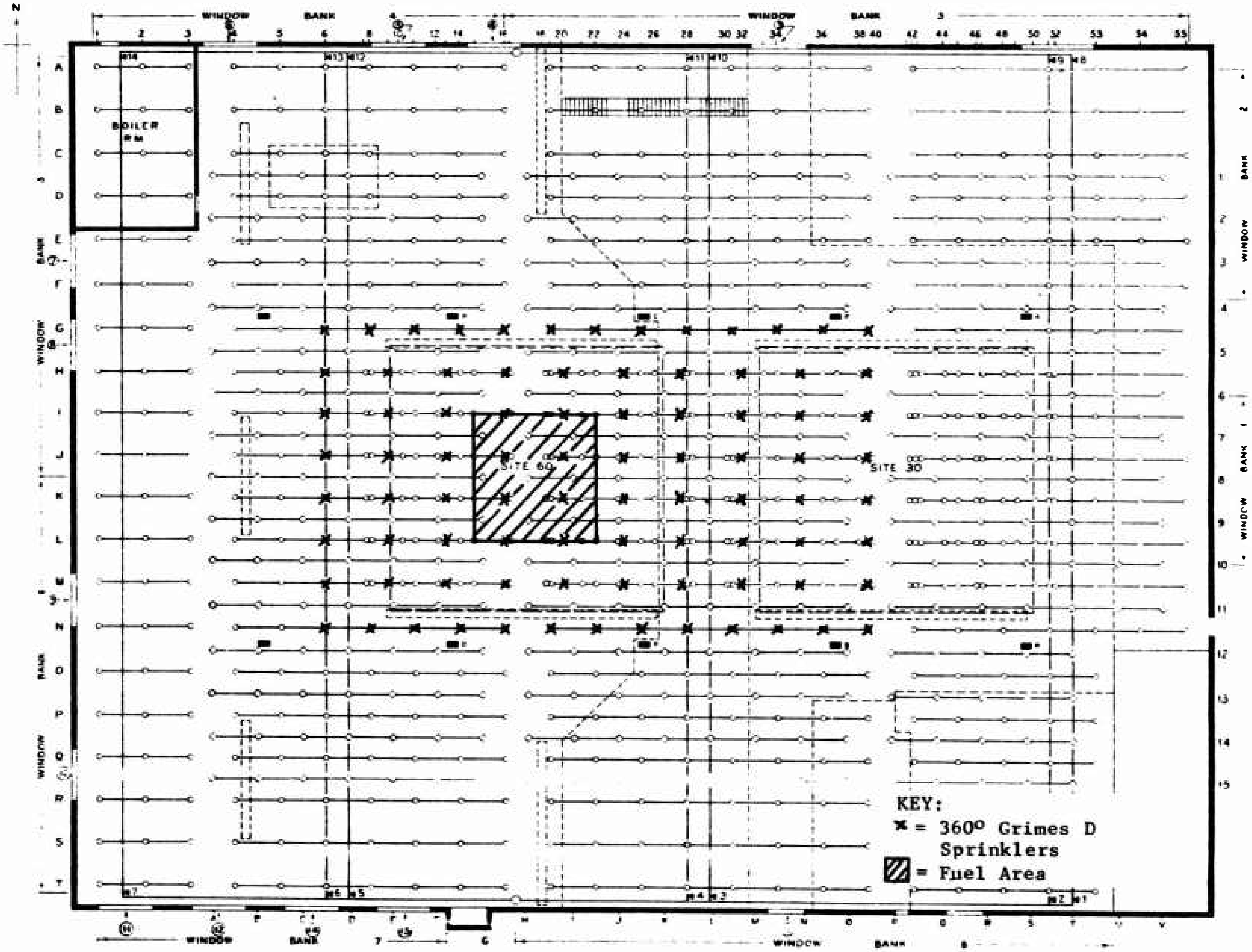

Figure 4 Closed Head Sprinkler System

as Test No. 8, using as a 6-percent AFFF agent, a carefully proportioned mixture of leftover AFFF agents each of insufficient quantity for the conduct of a test.

Complete test design parameters and results appear in Table I.

Several points should be noted before referring to the table:

1) Control and extinguishment times require human judgment. The range of observations of two or three qualified observers are, therefore, presented.

2) Two refractometers were used by two observers in each test. The concentrations presented are averages generated from the four resulting observations.

3) Two critical readings, control and extinguishment times are to a very large degree dependent upon the total hydraulics of the test suppression system and, therefore, have their most significant meaning as a relative measure from one test to another. Since the hydraulics of actual installed systems will be different, it should not be assumed that the same control and extinguishment times would be obtained. Because the test system incorporated only a segment of the actual number of sprinklers expected in a hangar installation and because the FMRC water system hydraulics are especially good, the times obtained for control and extinguishment could represent minimums.

The following significant observations can be made from the test results:

1) FC-203 at 0.125 gpm/ft^2 is approximately 40 percent less effective than at 0.16 gpm/ft^2 (2) in achieving 90-percent control and is dramatically less effective in providing extinguishment once 90-percent control has been achieved.

2) With an application rate of 0.1 gpm/ft^2, oscillating monitor nozzles, if unobstructed and designed to cover all potential floor fire areas, are the most effective and practical method known of extinguishing a spill fire. However, it is significant to compare the results of Tests 3 and 6 to the results of Test 4. An unplanned 10-lb pressure drop in Test 4 caused a 15-ft reduction in nozzle range resulting in 90-percent control and extinguishment time three to four times those observed in Tests 3 and 6.

TABLE I

FIRE TEST SUMMARY, DESIGN PARAMETERS

Test No.	1	2	3	4	5	6	7	8
<u>TEST DESIGN PARAMETERS</u>								
Suppression System	Deluge	Deluge	T/N**	T/N & closed head	Closed head	T/N	Deluge	Closed head
Agent	FC-203	FC-203	FC-203	FC-203	Water	FC-200	FC-200	***
Design Concentration	3.4%	3.4%	3.4%	3.4%	—	6.0	6.0	6.0
Sprinkler Heads	Grinnell SSU-3	Grinnell SSU-3	NA	Grimes D (360°F)	Grimes D (360°F)	NA	Grinnell SSU-3	Grimes D (360°F)
Number of Heads	48	48	NA	86	86	NA	48	86
Sprinkler Spacing (ft^2/hd)	130	130	NA	130	130	NA	130	130
Solution Flow/Head (gpm)	16	16	NA	21	21	NA	16	21
Design Density (gpm/ft^2)	.125	.125	NA	0.16	0.16	.1	.125	.16
EHP*(psig)	8	8	NA	14	14	NA	8	14
T/N Pressure (psig)	NA	NA	80	80	NA	80	NA	NA
T/N Flow (gpm)	NA	NA	450		NA	450	NA	NA
T/N Design Density (gpm/ft^2)	NA	NA	0.10	0.10	NA	0.10	NA	NA
Total Solution Flow (gpm)	780	780	450	Depends on number of heads fused	Depends on number of heads fused	450	780	Depends on number of heads fused

* EHP = End Head Pressure

** T/N = Turret Nozzle

*** 6% solution consisting of mixed 3M Co. products

TABLE I (CONT'D)

FIRE TEST SUMMARY, TEST RESULTS

Test No.	1	2	3	4	5	6	7	8
Density (gpm/ft^2)	.125 decay to 0.06	.125	~0.1	~0.16 overhead <.1 T/N	0.16	0.1	0.125	0.16
Suppression System On	0:10	0:14	0:10	~0:10	0:19 1st AS	0:12	0:15	0:32 1st AS
Visible Foam Flow	0:40-0:41	0:25-0:28	0:15-0:17 T/N	0:12-0:15 T/N (spkr. time unknown)	0:23-0:25	0:15-0:20	0:25	0:37
75% Control	2:30-2:50	1:50-2:00	0:20-0:25	1:15-1:30	-	0:25-0:32	2:20-2:25	2:00-2:05
90% Control	3:00-3:05	2:05-2:25	0:25-0:30	1:30-1:55	-	0:33-0:39	2:30-2:40	2:10
Extinguishment	No	3:15	0:50-0:55	2:15-2:30	-	0:40	2:50-3:10	2:30
Refractometer Readings % Time 0:00	2.3	3.5	2.8	2.8	0.4	5	6	9.5
0:30	9.9	3.6	3.1	3.3	0	5	5.5	6.7
1:00	3.5	3.6	3.1	3.1	0	4.8	5.8	4
1:30	3.5	3.5		3.1	0		5.5	3.8
2:00	3.5	3.5		3.1	0		5.8	4
3:00	3.5	3.5					4.8	
4:00	3.5							
5:00	3.5							
Actual Pressure (psig) Overhead Syst	8.4-2.1(decay)	8.4	NA	14	21	NA	8	21
T/N	NA	NA	80	70	NA	80	NA	NA
Expansion Ratio	1.9	2.3	-	-	-	-	1.7	2.1
75% Drainage Time	<0:30	1:10	-	-	-	-	<1:00	2:11
Time Between Visible Foam and 90% Control	2:20	1:40-2:00	0:10-0:15	~1:30	-	~:20	~2:15	1:23
Time Between 90% Control and Extinguishment	NA	1:00	0:25	0:35-0:45	-	~.:05	~:25	:20
Comments	1)Foam shut off at 5:00 2)Fire area initially larger than 900 ft^2 by 10-15%		1)Fire was pushed slightly outside 30'x30' boundaries by T/N action	1)One sprinkler operated 2)Nozzle's range was only to center of fire Fire extended beyond plastic dike by~5 ft on S. side. Fire on S. side extinguished by flowing foam. 3)Total solution flow 435 gpm	1)73 out of 86 heads operated 2)Total solution flow 1520 gmp			1)40 out of 86 heads operated 2)Total solution flow, 832 gpm

NOTE:

All times not otherwise noted, in minutes and seconds from Ignition

3) No truly significant differences in fire suppression effectiveness exist between FC-203 and FC-200 for the conditions tested.

4) Great promise exists for the closed head sprinkler system in hangars. In Test 4, only one sprinkler head operated due to the rapid extinguishing effect provided by the oscillating monitor nozzle, in spite of its unusually long control time. In Test 5, 73 of the 86 installed sprinklers operated (Figure 5) and provided enough ceiling cooling such that the remainder did not fuse, despite the fact that the plain water was totally ineffective in controlling the fire. In Test 8 only 40 of the 86 installed sprinklers operated (Figure 6) providing control and extinguishment times comparable to previous 6-percent AFFF deluge system tests. These observations point to a potential tremendous savings in water demand for closed head AFFF systems as compared to AFFF deluge systems.

Figures 7 and 8 show a typical fire test at ignition and at full intensity.

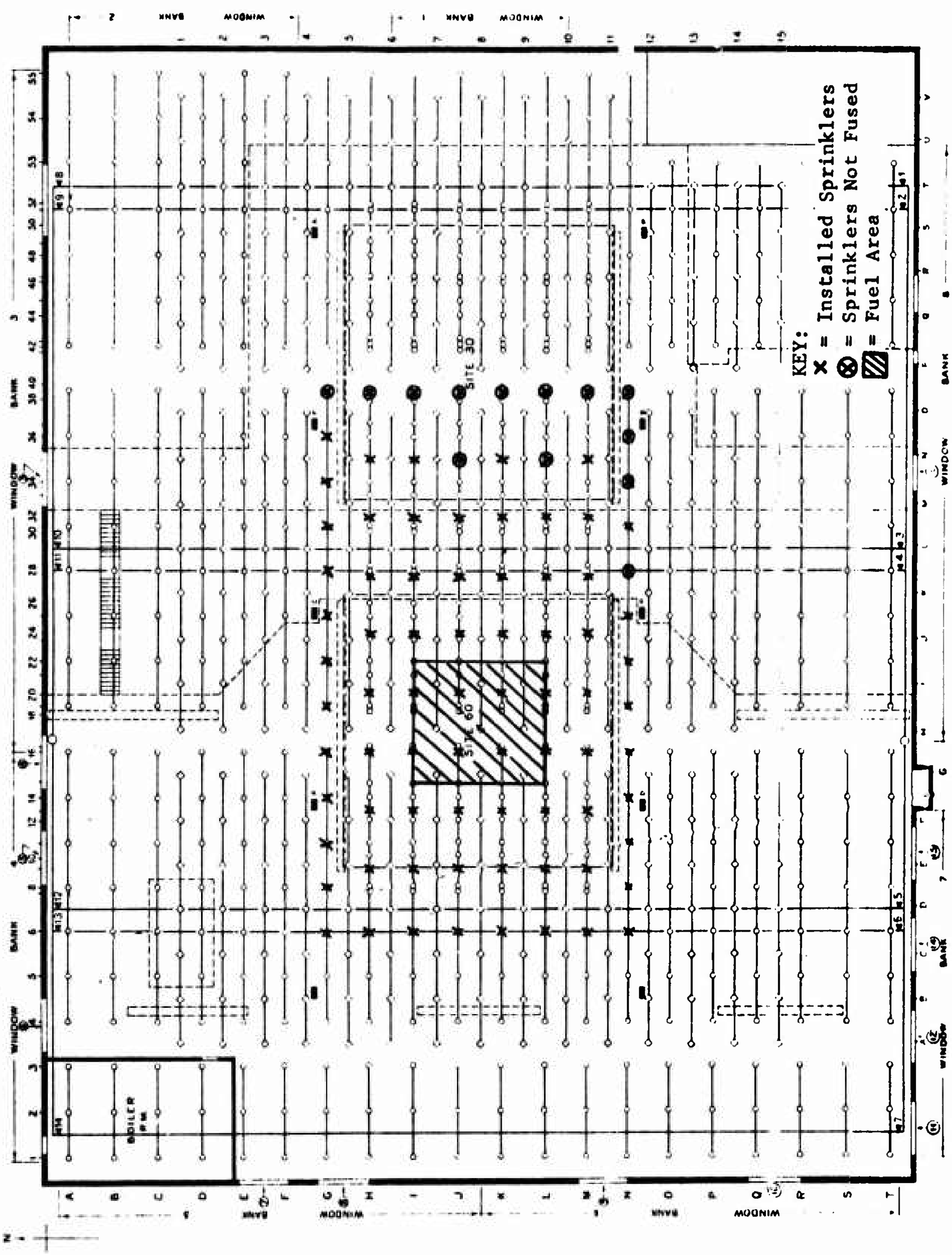

Figure 5 Sprinklers Operated In Test No. 5

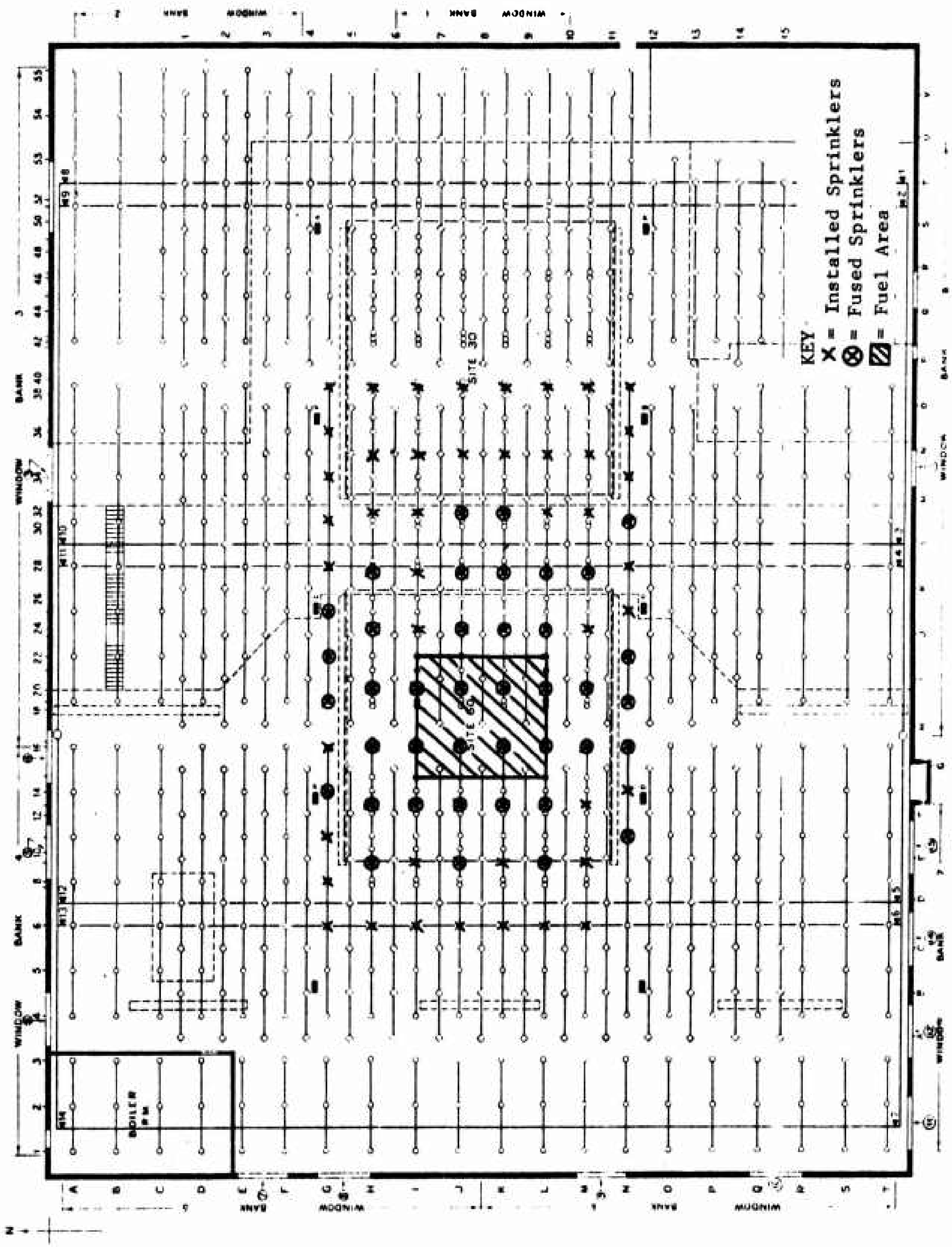

Figure 6 Sprinklers Operated In Test No. 8

Figure 7 Typical Test At Ignition

Figure 8 Typical Test In Progress

SECTION IV

LABORATORY EVALUATION OF THE ATTENUATION OF AFFF DISCHARGE

4.1 TEST PROCEDURE

An attempt was made to measure the suppression effectiveness and stability to heat and combustion products of three different brands of AFFF. The brands will be referred to as "X, Y, and Z." X and Y are 3-percent formulations while Z is used at 6 percent. AFFF was generated through a laboratory-scale, non-air aspirating nozzle and allowed to flow down an incline onto a 1-ft^2 pan. In order to generate a base line, non-fire foam flow tests were first conducted. A series of heptane fire tests were then run with 15-sec preburn. The freeboard was 1 in. The nozzle pressures selected were 15, 20 and 25 psig. Generally, four tests at each pressure were conducted. 50- and 90-percent control times were measured from the instant foam entered the pan.

4.2 TEST RESULTS

Non-fire tests consistently showed that 90-percent coverage of the fuel surface occurred in approximately 30 sec.

Fire test results are shown in Figures 9, 10 and 11 and in Table II. The 90-percent control times were found to be more than twice as long as the 50-percent control times with only two exceptions in 365 pairs of observations.

Spot checks of the expansion ratios and drainage times showed that these two properties were in good agreement with data obtained from full-scale tests involving standard sprinkler deluge systems.[1,2]

Longer times, on the average, were required for 50- and 90-percent control by agent X than by the other two AFFF agents. These longer times recorded for X are significant for 15 psig. Dissimilarities in control times between agent X and other agents were also observed earlier in full-scale tests.[1,2]

The time required to achieve 90-percent coverage under non-fire conditions (av. 30 sec) was in all cases less than the time required by agents X and Z to achieve 90-percent control. Agent Y, for the most part, consistently achieved 90-percent control in less time than the other two agents. Agent Y achieved

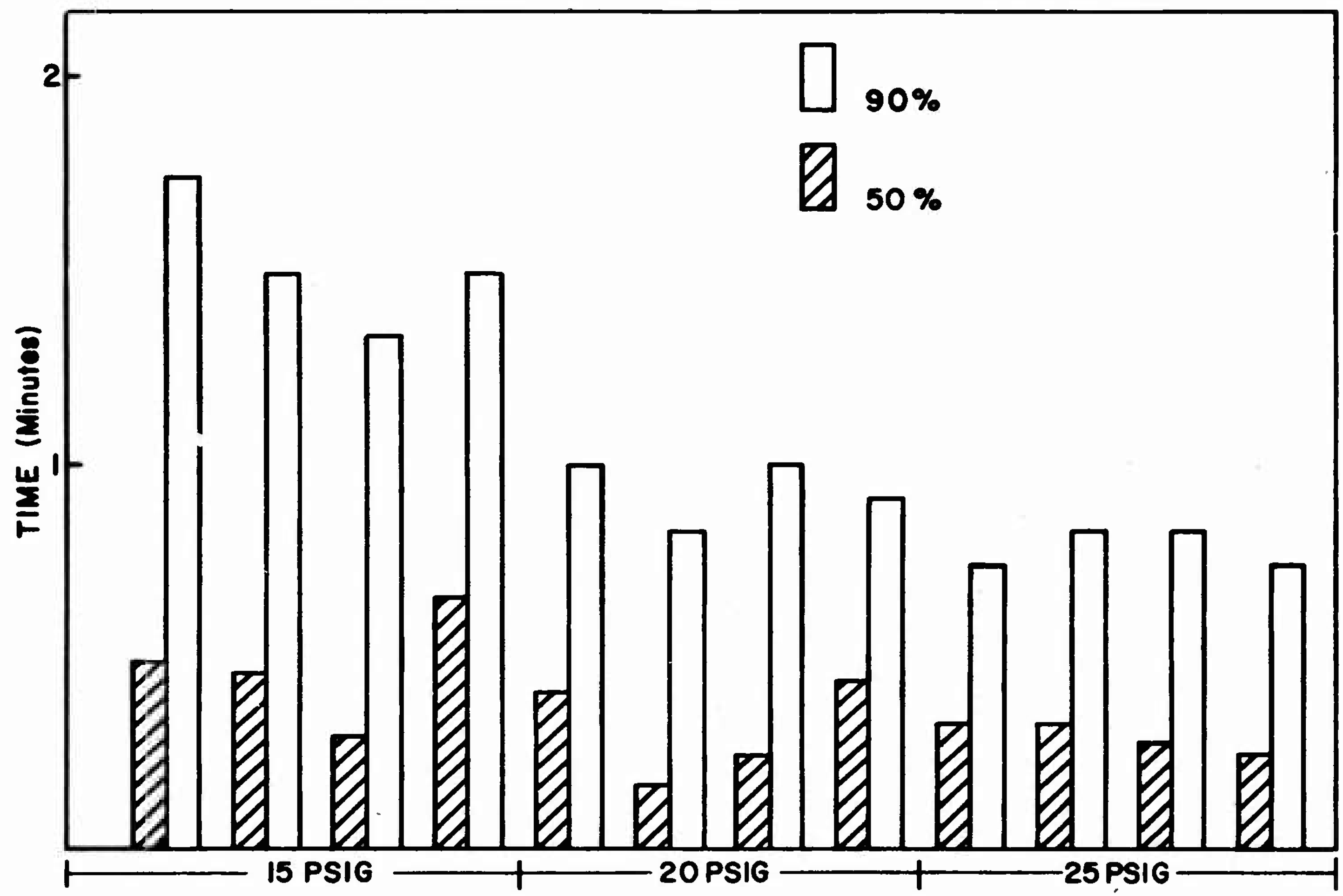

Figure 9 50-Percent And 90-Percent Control Times: Agent X

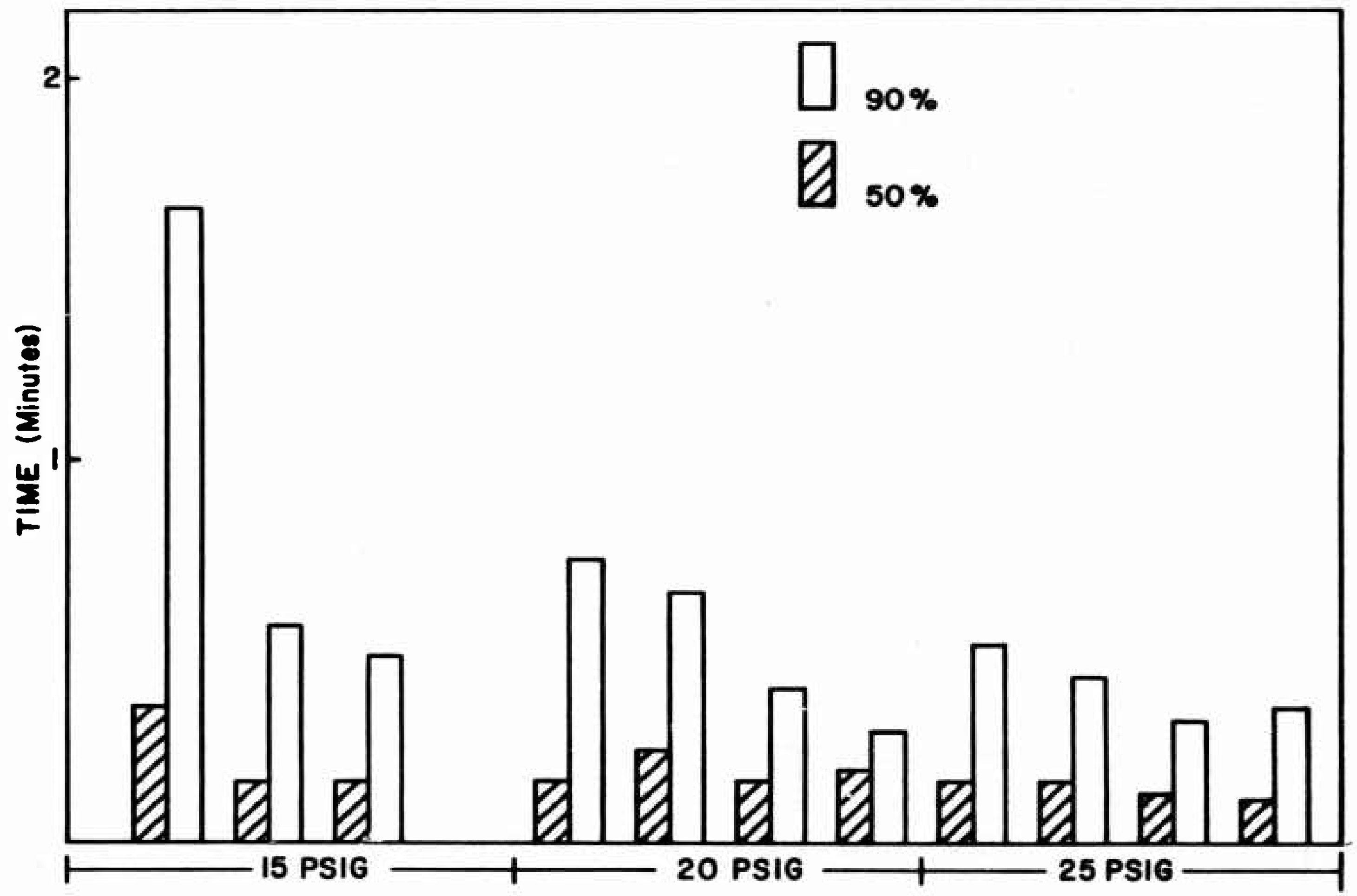

Figure 10 50-Percent And 90-Percent Control Times: Agent Y

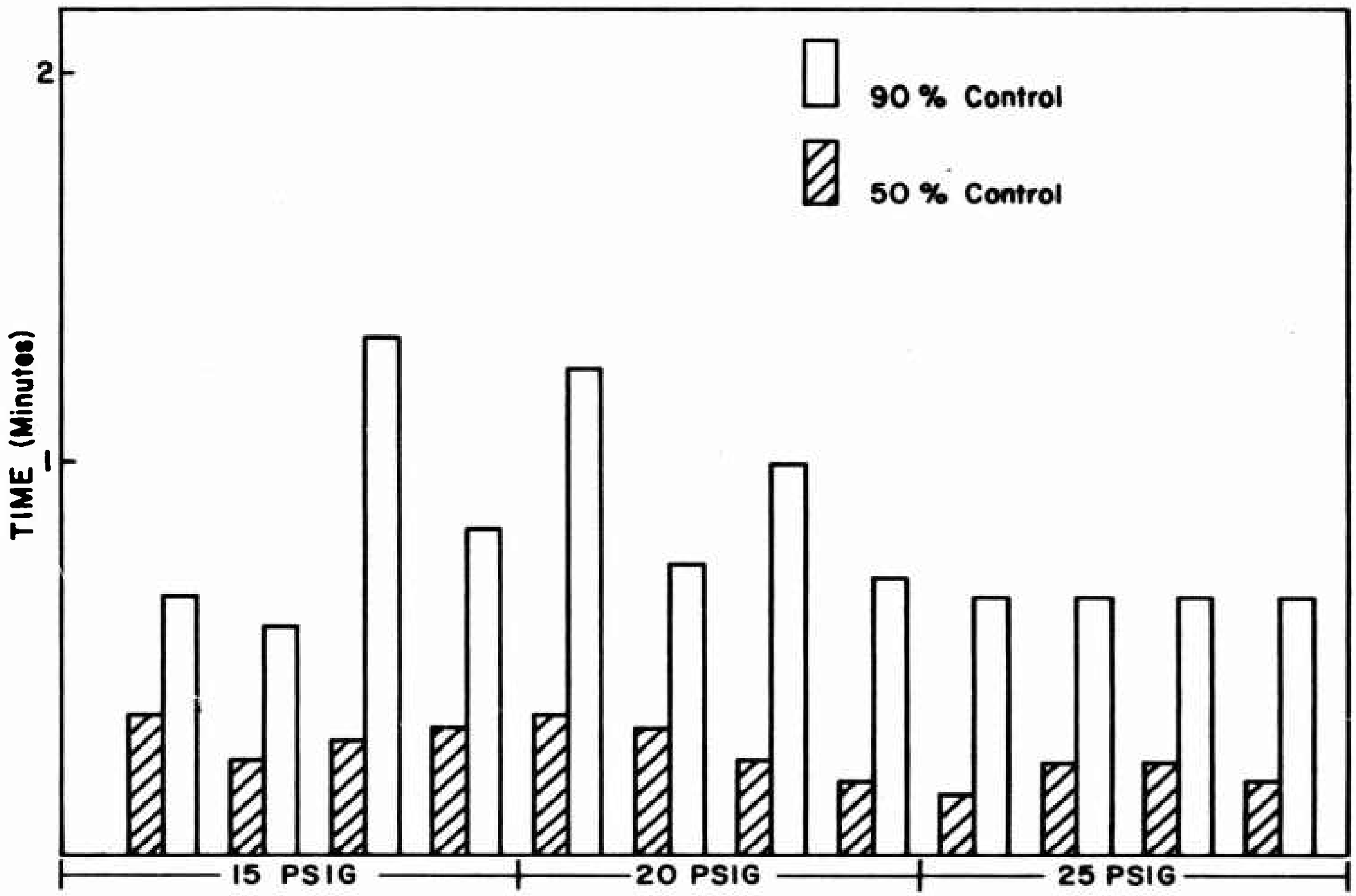

Figure 11 50-Percent And 90-Percent Control Times: Agent Z

TABLE II

50 PERCENT AND 90 PERCENT CONTROL TIMES

Agent	Pressure (psi)		Control Times (sec) 50%	90%
X	15		30	105
X	15		28	90
X	15		18	80
X	15		40	90
		Average	29	91.25
X	20		25	60
X	20		10	50
X	20		15	60
X	20		27	55
		Average	19.25	56.25
X	25		20	45
X	25		20	50
X	25		17	50
X	25		15	45
		Average	18	47.45
		Agent Average	22.1	65
Y	15		22	100
Y	15		10	35
Y	15		10	30
		Average	14	35
Y	20		10	35
Y	20		15	40
Y	20		10	25
Y	20		12	18
		Average	11.75	29.5
Y	25		10	32
Y	25		10	27
Y	25		8	20
Y	25		7	22
		Average	8.75	25.25
		Agent Average	11.3	34.9
Z	15		22	40
Z	15		15	35
Z	15		18	80
Z	15		20	50
		Average	18.75	51.25
Z	20		22	75
Z	20		20	45
Z	20		15	60
Z	20		12	43
		Average	17.25	55.75
Z	25		10	40
Z	25		15	40
Z	25		15	40
Z	25		12	40
		Average	13	40
		Agent Average	16.3	49

90-percent control time in an average of 35 sec, compared to 65 sec for agent X and 49 sec for agent Z. These observations suggest that the superior performance of agent Y is due to its greater resistance to breakdown by smoke and other reaction products and to thermal decomposition.

SECTION V

AFFF FIRE PLUME PENETRATION VERSUS FOAM PARTICLE SIZE

The assault of foam against unobstructed 900 ft^2 pool fire tests in FMRC's 60-ft high test facility has always been observed to occur at or near the edge of the pool when the foam is generated by deluge systems. The fact that this type of peripheral attack is sufficiently effective to reduce the fire area to 10 percent of its original size within 1 to 2 min at designed foam discharge rates of 0.16 to 0.25 $gal/min/ft^2$ underscores its great superiority over ordinary water. The peripheral attack is, of necessity, the only suppression mode available to the foam because the updraft velocities of the fire are too high at the centerline of the plume to permit any penetration until the fire becomes relatively small.

If we examine this mode of suppression in more detail, we find that one or both of two separate mechanisms can be operative. The first mechanism is the impacting of falling foam particles on the fuel surface and the subsequent coalescence of these impacted particles to form a vapor arresting blanket. The second mechanism is the flow of foam from the perimeter toward the center of the fire. The flow rate depends on how much foam has been deposited and on the hydraulic head available to drive it.

To obtain even a rough answer to the question - how much foam can fall within the perimeter of the pool fire? - we must be able to define numerically the following quantities:

1) The terminal velocity of the foam particles; and
2) The velocity distribution or velocity profile of the fire plume.

The terminal velocity of a particle in free fall (i.e., the maximum free-settling velocity it can reach) is attained when the gravitational forces on the particle are exactly counter-opposed by aerodynamic drag.

The equation relating these factors to the terminal velocity, U_t is

$$U_t = \left(\frac{2gm_p(\rho_p - \rho_a)}{\rho_a \rho_p A_p C_o} \right)^{1/2} \tag{1}$$

where g is the gravitational constant, m_p is the mass of the particle, ρ_p and ρ_a are the densities of the particle and the ambient air, respectively, A_p is the projected area of the particle and C_o is a drag coefficient.

For the case of rigid spherical particles, eq (1) can be simplified to give

$$U_t = \left(\frac{4\ g\ D_p\ (\rho_p - \rho_a)}{3\ \rho_a\ C_o} \right)^{1/2} \tag{2}$$

where D_p is the diameter of the particle.

Now, with any particle moving in an air stream there is a dimensionless number associated with it called the Reynolds number, which is very convenient to characterize flow conditions. This number is defined as

$$N_{Re} = \frac{V_p\ D_p}{\nu_a} \tag{3}$$

where V_p is the velocity of the particle and ν_a is the kinematic viscosity of the air. (ν_a, in turn, is equal to the absolute viscosity (μ) of the air divided by its density, ρ_a)

If a large particle is moving with a relative high velocity such that

$$10^3 \leq N_{Re} \leq 2 \times 10^5,$$

then the value of C_o for spheres has a relatively constant value of 0.44, and eq (2) becomes

$$U_t = 1.74 \left(\frac{g\ D_p\ (\rho_p - \rho_a)}{\rho_a} \right)^{1/2} \tag{4}$$

This range of Reynolds numbers is sometimes called the "Newton's Law" region.

If $0.3 \leq N_{Re} \leq 1000$, then C_o can be approximated by

$$C_o = \frac{18.5}{N_{Re}^{0.6}} \tag{5}$$

For a 3 mm water drop, ignoring the deformation effect, we can estimate its terminal velocity through eq (4); i.e., for $C_o = .44$, $D_p = 9.85\times10^{-3}$ ft(3mm), $\rho_a = 7.5\times10^{-2}$ lb/ft^3, $\rho_p = 62.4$ lb/ft^3 and $g = 32$ ft/sec^2,

$$U_t = 28.2 \text{ ft sec}^{-1}$$

Let us now determine the Reynolds number:

$$N_{Re} = \frac{V_p D_p \rho_a}{\mu} = \frac{(28.2)(9.85\times10^{-3})(7.5\times10^{-2})}{1.45\times10^{-5}}$$

$$N_{Re} = 1430$$

Therefore, we may conclude that, for the size of the particle selected, we are in the low end of the Newton's Law Region and that eq (4) holds. However, for particles of 1 mm or less, we would expect the terminal velocities predicted by eq (4) to be too high.

Carefully performed experimental work by Gunn & Kinzer[3] on the terminal velocity of water drops indicates that for drops with $D_p = 3$ mm, the measured value of U_t is 26.6 ft/sec, which is about 10 percent less than the theoretical terminal velocity. Yao and Kalelkar[4] have made more refined calculations on drop terminal velocities which allow for deformation and have shown that the terminal velocities of large drops (5-10 mm dia) approach a constant value of 32-33 ft/sec. However, as may be seen in Table III, the experimental values of Gunn & Kinzer[3] are lower than the corresponding theoretical values and, in fact, terminal velocities of drops with diameters larger than 6 mm were not reported by these workers because the drops were too unstable and tended to break up into smaller sizes.

TABLE III

COMPARISONS BETWEEN THE THEORETICAL AND EXPERIMENTAL TERMINAL VELOCITIES FOR LARGE WATER DROPS

Diameter D (mm)	Theoretical Terminal Velocity (ft/sec) (Ref 4)	Experimental Terminal Velocity (ft/sec) (Ref 3)
1	18.5	13.3
2	25.1	21.3
3	28.8	26.6
4	31.2	28.9
5	32.2	30.5
6	32.8	30.9
7	32.8	
8	32.8	The drops were too
9	32.5	unstable for careful
10	32.2	experimentation

These velocities are plotted in Figure 12.

In the above exercises on water drop dynamics our objective is to reason by analogy, since nothing is known about the drag properties of foam particles. Basically, we are endeavoring to establish a credible hypothesis that, if the highest terminal velocity (either experimentally or theoretically determined), of the largest stable water drops known cannot exceed 30-33 ft/sec, then it is doubtful if particles of foam, which are, at most, only half as dense as water, can attain terminal velocities which are any higher.

In the absence of wind (forced convection) or obstructions, the thermal plume (column of hot gases and smoke) rises almost vertically above the fuel surface in roughly the shape of an expanding cone. Such plumes are almost invariably turbulent and the fires which generate them exhibit pulsating or transient upward movement of flame fronts. Flame tips may break away from the primary flame region. Maximum flame temperatures,which are located at

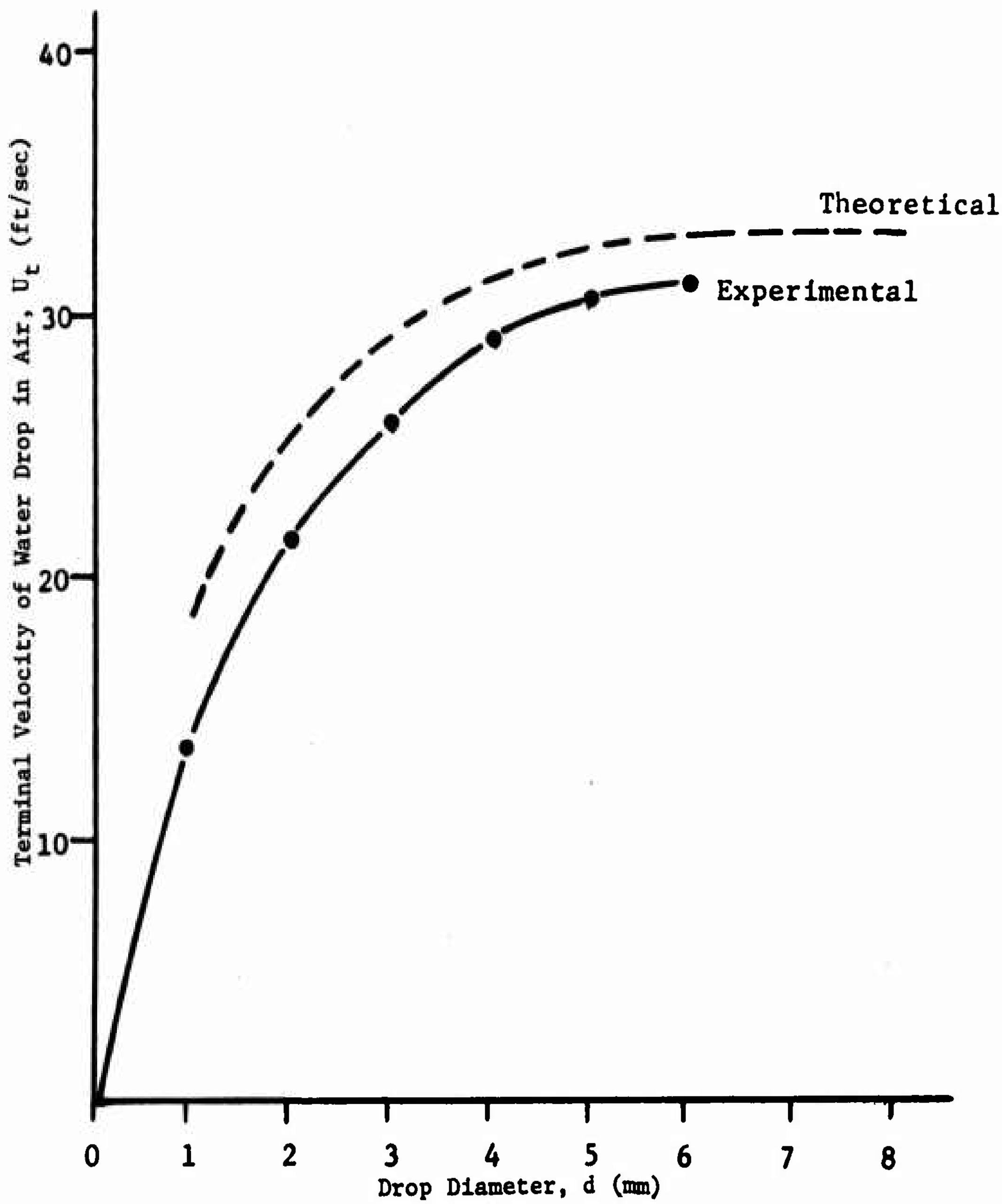

Figure 12 Terminal Velocity of Falling Drop

about 1/2 ~ 2/3 of the flame height, can be expected to be in the neighborhood of 1600°F. Maximum plume velocities may range up to 70 ft/sec for large spill fires. The highest velocities can be found somewhere below the flame tips (which are typically found at elevations about two times the diameter of the pool area); the highest velocities are found above the center of the pool and are known to decrease rather slowly with elevation. However, plume velocities decrease sharply along the radius toward the perimeter.

Well known plume theory (5)(6)(7)(8) predicts the following dependence:

$$V_o \propto \left(\frac{Q_c}{z+a} \right)^{1/3} \tag{6}$$

$$\Delta T_o \propto \frac{Q_c^{\;2/3}}{(z+a)^{5/3}} \tag{7}$$

where V_o = centerline velocity

Q_c = heat release rate

z = height above fuel source

a = a constant for a given fuel area

ΔT_o = centerline excess temperature, $T_o - T_\infty$

T_∞ = ambient temperature

For simplicity, Q_c may be approximated by Q, the theoretical heat release rate for total conversion of the hydrocarbon fuel to CO_2 and H_2O.

Equations (6) and (7) may then be combined to give the relationship:

$$V_o = C \left(Q \Delta T_o \right)^{1/5} \tag{8}$$

where C is a constant. FMRC has found that the value of C is approximately 0.7 (ft/sec)x(Btu °F/min)$^{-1/5}$.(9)

For pool fires larger than 3 ft in diameter, Q is directly dependent on the area of the burning fuel surface. It has been reported by Fitzgerald(10) that the average burning rate (before reaching a steady state combustion rate) of 0.25 in. deep JP-4 pan fires is 0.215 lb/min/ft^2*. Assuming 18,000 Btu/lb

*A 0.25 in. depth of fuel is approximately 140 gal spread over 900 ft^2.

for complete combustion, the heat release rate of such fires is 3,880 Btu/min/ft^2. The maximum centerline plume velocity of liquid hydrocarbon fires may now be written as a function of area, A:

$$V_o = (0.7) \left[3880 A \Delta T_o \right]^{1/5} = 3.7\ \Delta T_o^{\ 1/5}\ A^{1/5} \qquad (9)$$

From experimental data obtained from liquid hydrocarbon fuel fires, substituting the flame tip temperature of $\Delta T_o = 1000°F$ and $A = 900\ ft^2$, it can be shown that $V_o = 56$ fps. This value of V_o is similar to the updraft velocities measured at 60-ft elevations above 900 ft^2 JP-4 fires in which temperatures fluctuated around 1500-1700°F. As a result, none of the particle sizes listed in Table III could achieve direct penetration through the centerline of such fires.

However, as mentioned earlier, the vertical component of the plume velocity is not constant over the fire area; it is highest at the centerline and decreases toward the plume/ambient air boundary. Figure 13 shows some experimental measurements of fire plume velocity made by FMRC(11) at various distances from the centerline of heptane and wood fires. It is seen that the velocity profile is described by a bell-shaped curve. One should keep clearly in mind that, although particles which can be shown by theory to be incapable of penetrating the updraft of a fire at its centerline (where such updrafts have the highest velocities), they may penetrate to the fuel source at some radial distance from the centerline.

A more detailed examination of Figure 13 shows just how rapidly the vertical velocity decreases with distance from the centerline. The maximum plume velocity measured for the 12-gpm heptane spray, equivalent to a 270 ft^2 JP-4 pool fire, is $V_o \simeq 52$ fps. A velocity of 1/2 V_o is found at a distance, r, of only ~3 ft from the centerline. Such a rapid radial fall-off in velocity explains why foam deluge systems have always been observed to suppress fuel fires through a constricting action which begins at the original boundary of the burning fuel source and works its way toward the center. It

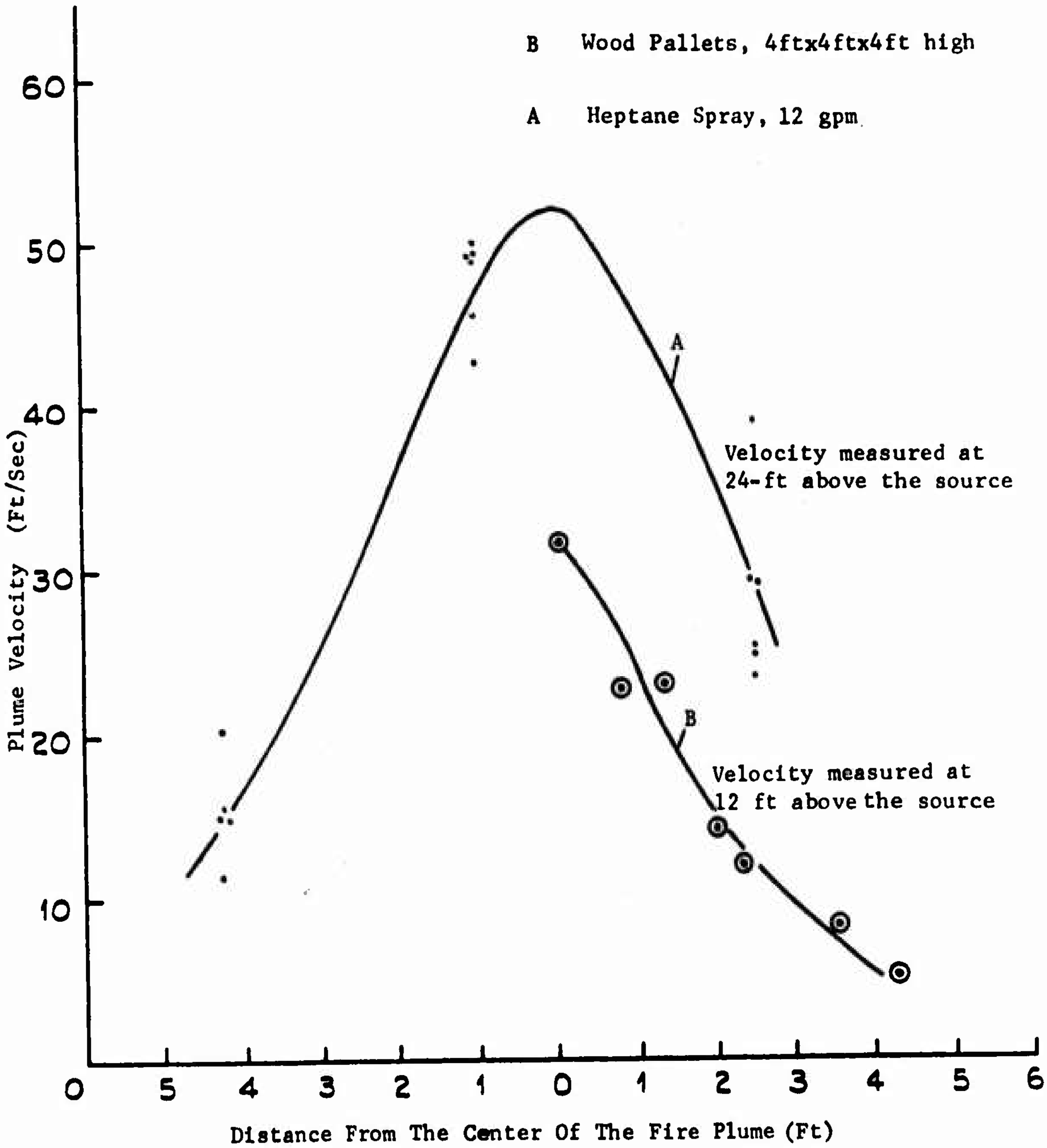

Figure 13 Plume Velocity Profile Measured For Large-Scale Freeburn Fire Tests During The Period Of Approximate Constant Burning Rate

is this path of least resistance which is followed in all cases. Unfortunately, the theoretical equations describing the velocity profile of a fuel fire near its source are currently unknown. In these lower regions of the plume the fluid mechanical equations must take account of reacting gases, which adds greatly to the complexity of the task.

Figure 14 illustrates an idealized fire plume generated by a circular fire source. The region where traditional plume theory works well is identified as the range from slightly below the flame tips to heights just below the ceiling. The constant, a, identified in eqs (6) and (7), is the distance beneath the actual fire source where the boundary lines of the plume cone converge; that point of convergence is called the "virtual source". Also shown in Figure 14 is a curve showing the general behavior of the centerline velocity. It is seen that this velocity increases from the source up to a maximum at the region of the flame tips and decreases at higher elevations.

It is the lower region that remains poorly defined by theory. Empirically, it is generally found that this region is characterized by a "necking in" of the plume and that the vertical velocity profile is not bell-shaped, but rather exhibits a depression at the centerline.

Assuming that the foam particles generated from standard sprinklers have a weight median diameter of 0.25 in. and expansion ratios averaging 2:1*, then, from eq (4), more than 50 percent of the foam particles can penetrate a 30 fps fire plume at an elevated temperature of 1000°F.**

Taking the same fuel surface area of 900 ft^2 selected in the FMRC tests described in this report, we can make some rough calculations to estimate the extent of the fuel area beneath the plume where the foam particles could penetrate. We make the simplifying assumptions that 1) the fuel area is

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* This assumption is unfounded but represents the best information available based on measurements of bulk quantities of foam, i.e., samples much larger than single or several droplets.

**The density of air at 1000°F is significantly less than that of 70°F air. Therefore, the terminal velocity of a particle in such a rarefied atmosphere would be somewhat higher than at 70°F. Such differences, however, do not invalidate the general conclusions presented above.

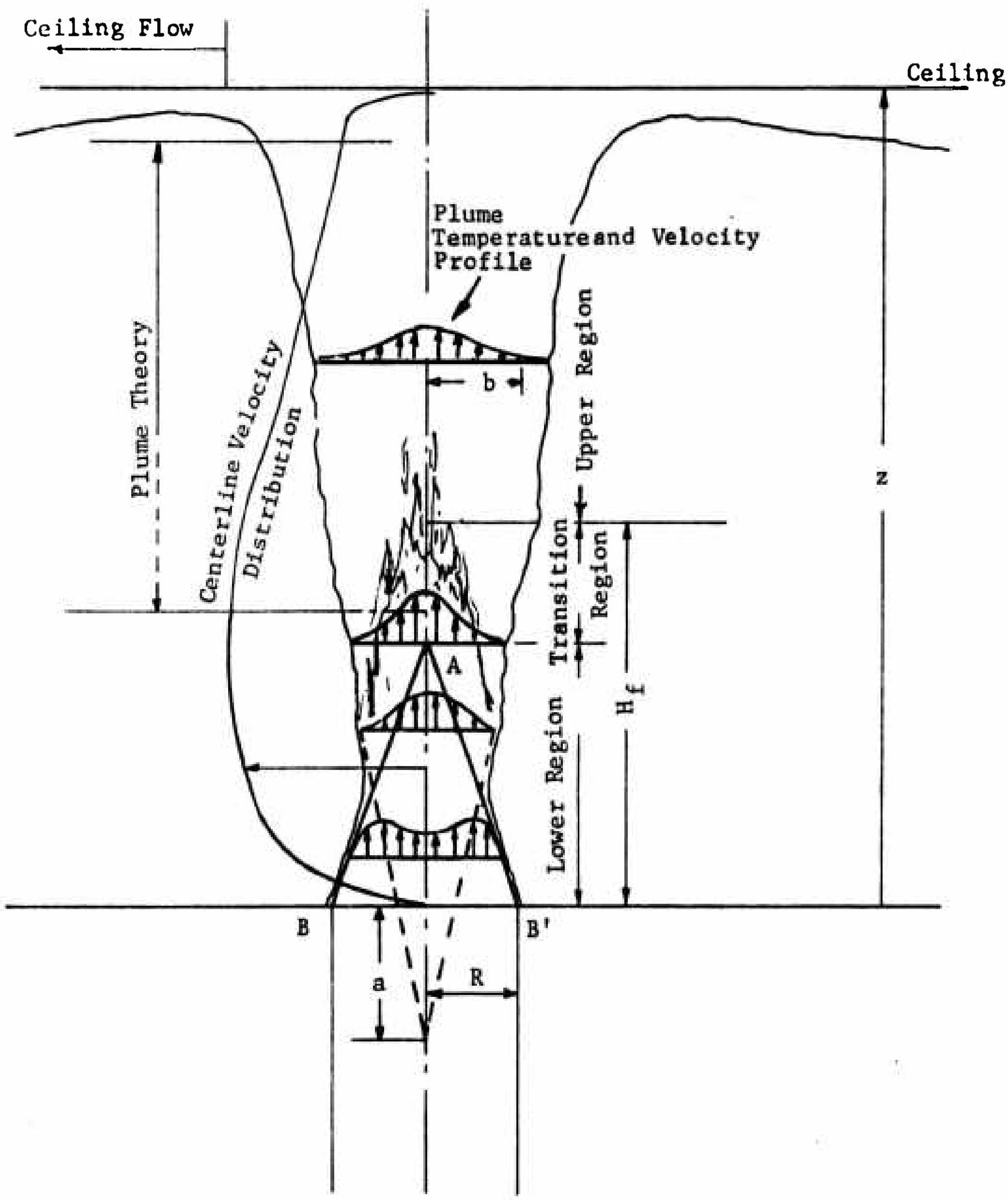

Figure 14 Illustration Of The Physical Characteristics Of Fire Plume Generated From A Circular Fire Source

circular, 2) the velocity profile is symmetrical about the center, with a maximum updraft velocity at this center and zero velocity at the perimeter, and 3) the velocity dependence on radial distance can be approximated by a straight line rather than a bell-shaped curve. The calculations show that about 75 percent of the fuel area is covered with a fire plume velocity less than 30 fps. Therefore, we can show that for a circular 900 ft^2 fire (radius = 17 ft) the percentage of the surface that can receive more than 50 percent of the designed discharge density is estimated to be 75 percent.

Of course, as the suppression of the fire by foam continues, the exposed fire area should shrink, allowing the percent of area penetration to increase.

During the early stages of a pool fire, the burning rate increases until it reaches a steady state. The time to reach the steady state burning rate for JP-4 increases with fuel depth. It has been reported[10] that a 0.25-in. deep JP-4 fire in a 20-ft^2 pan* reaches a steady state rate of 0.534 $lb/min/ft^2$ in 1.6 min. It is, thus, evident that the longer a fire is allowed to burn freely (until steady state is reached), the more difficult it will be for a foam deluge system to suppress it.

For practical application, the results generated above should be viewed on an order of magnitude basis. The equations cannot be expected to give rigorous answers because of an inability to treat several important factors. First, high temperature environments and high levels of soot formation may cause degradation of the foam such that particles theoretically predicted to penetrate a given plume may, in fact, be destroyed before reaching the fuel surface. Secondly, an unknown fraction of the foam is entrained at the base of the plume by forced convection. This foam may ultimately come to rest on the fuel surface where it can assist in extinguishment. If entrainment did not exist, these foam particles would fall outside the fire area. Thirdly, the foam liquid on the surface helps to cool the condensed phase and bring about a reduction in localized burning rate. Similarly, foam which is entrained into the flame zone, if evaporated, acts in a minor way to diminish the amount of energy in this zone which radiates back to the fuel surface for

*Pan wall height 12 in.; freeboard 2 in.; depth of fuel plus water 10 in.

further vaporization of fuel. These latter two effects lower the value of the burning rate. The assumption of a steady state burning rate, is therefore, invalid when suppression is underway. In addition, the drag coefficient in eq (4) is probably greater than 0.44 due to particle deformation; therefore, higher values of this coefficient would mean lower terminal velocities.

Perhaps of greatest importance to a basic understanding, is the actual particle size and expansion ratio distributions in the pattern of discharged foam particles. It is felt that a more rigorous treatment of parameters is outside the scope of existing theory and that even an empirical characterization would require a protracted and exacting test program.

In summary, a specific fire plume strength and foam particle size has been selected for the purposes of describing the penetrability of particles through the plume when such particles are generated by deluge systems above the flame tips of a 900 ft^2 circular-source liquid fuel fire. The study has shown that idealized spherical foam particles with diameters of 0.25 in. and expansion ratios of 2:1 should reach approximately 75 percent of the fuel surface. The predicted fuel surface region affording penetrability would be an annular ring, bounded by the outer circumference of the burning liquid and by an inner circumference where the terminal velocity of the foam is equal to the plume velocity.

SECTION VI
SUPPLEMENTARY LOW LEVEL FOAM SYSTEMS

6.1 GENERAL

The predominant system for protecting aircraft located inside hangars has been automatically actuated oscillating monitor nozzle systems designed to discharge protein, fluoroprotein or AFFF foams at application rates of 0.16, 0.16 and 0.1 gpm/ft^2, respectively. The preference for these systems has been based on several factors:

1) The ability to discharge foam to the protected area beneath the aircraft from distances in excess of 100 ft;

2) Optimum use of water;

3) The fact that low expansion foam does not prevent access to the aircraft;

4) The ability to combine the foam concentrate supply with that of a foam water sprinkler system, if provided; and

5) The ability to discharge foam and suppress fuel vapors or flush spilled fuel toward drains prior to ignition.

Other systems considered or used for supplementary protection are: 1) fixed monitor nozzles (non-oscillating) discharging various types of low expansion foam; 2) high expansion foam systems and 3) pop-up discharge devices located in the floor which distribute foam directly beneath the aircraft. Although these systems have excellent fire fighting potential, serious limitations associated with each make their use in a typical overhaul or maintenance hangar questionable.

6.2 FIXED MONITOR NOZZLES

Fixed monitor nozzles have not been used in hangars because of the need to locate the nozzles close to the aircraft. While these nozzles have suppression ability comparable to an oscillating monitor system, they cover a smaller area than oscillating nozzles and do not apply agent as uniformly. An unrealistic number of smaller nozzles or increased water demand would be required to

provide protection equivalent to an oscillating nozzle system.

In those hangars where fixed workstands, the hangar configuration or the aircraft parking arrangements permit installation of a fixed monitor nozzle system adjacent to aircraft, the nozzles could discharge in a spray pattern, thereby increasing the protected area per nozzle. At full spray patterns, however, the maximum reach of the nozzle is approximately 40 ft at pressures of 100 psi. However, in the limited cases where such a system might be installed, it would be a reliable and effective type of supplementary foam system. For example, field tests of oscillating monitor nozzle systems have shown a fairly high incidence of failure of the oscillating motors (both the water driven and electric types), which definitely downgrades the reliability of those systems. In addition, because oscillating nozzles are located at a remote distance from the aircraft, their discharge is more likely to be obstructed by portable equipment such as workstands, trucks, or other aircraft. Therefore, a fixed monitor nozzle system eliminates reliability problems associated with an oscillating motor and minimizes possible tampering with the nozzle angle of rotation, nozzle elevation, or other adjustment which could affect the original design of the system. Its close proximity to the aircraft makes it less likely that its discharge would be obstructed.

6.3 HIGH EXPANSION FOAM SYSTEMS

At least two major Type I hangars in the United States have been protected with high expansion foam systems in combination with water deluge systems. The advantages of such a foam system are that it discharges a large volume of foam over the entire hangar area while minimizing the water requirements. As the location of the system is generally at the hangar ceiling or roof, the discharge patterns are not compromised by the location of aircraft or workstands, or by intentional or accidental tampering with the generators. Counterbalancing this, however, are several important deficiencies. In order to provide a foam blanket beneath the aircraft within 30-45 sec, an overhead high expansion foam system is normally designed to discharge at extraordinarily

high rates (4-6 ft/min for 800-1000:1 expanded foam). Such rates could hinder personnel egress from the hangar and from the aircraft. To achieve a satisfactory level of personnel safety, the discharge would have to be delayed, thus potentially increasing damage to the aircraft. In addition, once the foam has been discharged, entering the hangar to secure the fuel leak and effect final mop-up of the fuel spill fire would be next to impossible (high expansion foam may extinguish three-dimensional JP-5 fires, but probably will not extinguish such fires in JP-4 fuels).[12] If fire spreads to the aircraft interior through open doors or compartments prior to control of the spill fire, the aircraft could be destroyed or severely damaged from an unchecked interior fire. Finally, equipment reliability of high expansion foam systems appears to be particularly suspect. Systems of the size and capacity required to provide aircraft protection in a large hangar involve an intricate network of detectors, electrical generators, intake, and heat/smoke vents, and associated pumps for water and foam concentrate supply. In order to assure equipment reliability, the systems must be discharged at periodic intervals (preferably not less than yearly), to validate system operation. As an example of the maintenance problem, in one hangar, only six of 11 generators and none of the heat/smoke or air intake vents operated properly during the first trip test of a system following the initial acceptance tests slightly more than three years earlier. When an identical system in the second hangar bay was discharged following maintenance designed to eliminate the failures witnessed in the first trip test, nine out of the 11 water supply valves failed to open properly, resulting in no foam discharge from those generators.

As a result of such problems, the major use of high expansion foam systems in hangars has been in the smaller type hangars (Type II) which do not require as complicated maintenance functions or have large concentrations of personnel typical of larger hangars.

6.4 FLOOR NOZZLE SYSTEMS

One of the earliest concepts for protecting the area beneath aircraft was the use of pop-up foam nozzles located in the floor directly beneath the aircraft. The major advantage of such systems is that they can be designed to discharge foam at a uniform rate over a designated area at relatively low pressures and water volume. According to the limited fire test data available, extremely rapid fire suppression can be achieved. For example, prior to installing a floor nozzle system using AFFF in the hangar of the Filton assembly plant for the Concorde, the British Aircraft Corporation (BAC) ran a series of outdoor fire tests having areas up to 2200 sq ft.[13] The nozzle system successfully extinguished the fires within 15-30 sec of system actuation.

Despite the potential effectiveness of a system installed in the floor, there are certain inherent reliability problems. Such systems can be compromised if nozzles are obstructed by portable equipment or by placement of tool boxes or other items which would prevent proper nozzle operation or discharge. Similarly, because spillage of various types of aircraft fluids is common (i.e., fuel, antifreeze, hydraulic fluids,etc.), the nozzles would have to be resistant to degradation from such fluids. Gaskets, O-rings, and lubricants (if any) would have to be compatible with a wide range of fluids. Alternatively, an intensive maintenance program would be required to assure regular inspection and replacement of parts which might degrade with time. Finally, nozzles and piping would require special caps to prevent accumulation of dirt, parts, or other obstructions in the discharge orifices which could interfere with agent flow. Such caps would have to withstand heavy loads that might be placed on them at periodic intervals and still operate at the design pressure. In testing with one prototype nozzle designed for use in a floor-mounted system, FMRC found that the cap which had been provided for protection did not operate, even when tested well above the system design pressure. Based on analysis of existing equipment, considerable design engineering is necessary before such a system can prove a viable means of protection for aircraft in hangars.

6.5 ACTUATION

Provision in National Fire Protection Association Code No. 409-Aircraft Hangars requiring automatic actuation of supplementary foam systems has generated concern over two points: 1) possible hindering of personnel egress from the hangar in the event of fire; and 2) the potential for an accidental discharge. As a result, there has been considerable reservation about using highly sensitive, rapidly responding detectors for actuating systems. In several instances where radiation detectors, such as those sensing infrared or ultraviolet emission, have been installed in hangars, the systems have been arranged to sound on alarm only, and have not been interconnected to the foam systems. In all cases, however, the systems are automatically actuated if the detection system for the primary protection system is tripped. The requirement for automatic operation developed from experience in actual hangar fires, where entrance of fire fighting personnel into the hangar was often impossible, regardless of whether the fires originated in, or involved, fuel spills, or originated and were entirely contained within the aircraft fuselage. In both cases, the dense black smoke and the intense heat prohibited effective fire fighting. For the same reasons, it was felt that manual operation of monitor nozzle systems would not be possible in all cases. Individuals would have to wear protective clothing and be equipped with self-contained breathing apparatus. These requirements would further compromise response time. Thus, in most cases, automatic actuation and operation was considered essential to achieving the design purpose of the supplementary system.

SECTION VII
INJECTION OF NON-POLLUTANT FIRE RETARDANTS

7.1 GENERAL

Reasons for ensuring environmental protection, including anti-pollution safeguards, are becoming increasingly numerous. It is evident, in comparison with past years, that in many geographic areas, the air, water and land have been changed for the worse. It has been suggested that the use of AFFF to suppress a large fuel fire may involve the possibility of contaminating water supplies, rivers, lakes and harbors. The AFFF's, which contain fluorochemicals and other surfactants[14], together with additional chemicals, such as anti-freeze, may cause undesirable temporary side effects if sufficient quantities should drain or spill into waterways. The most conspicuous effect of such a spill would probably be visible foam or froth formed under mild agitation. Because of the great dilution, and infrequent and short duration, of such run-off this problem is not considered serious. Less conspicuous is the potential for reducing the effectiveness of waste treatment facilities since large quantities of AFFF can stop the multiplication of bacteria in the digestion process of such facilities. However, in hangar facilities where such a treatment plant is involved, retention and gradual dispersement of run-off water should eliminate the problem.

The alternatives to the use of AFFF in protecting aircraft hangars are:

1) Use of water additives or other substances (other than low expansion foams) which may be judged to be non-polluting or less deleterious pollutants compared to AFFF; and

2) Use of other low expansion fire suppressant foams which may be more biodegradable.

7.2 WATER ADDITIVES

We know of no agent in this category which would be operationally feasible to inject into sprinkler systems and which would afford a fire suppression capability even close to that which has been proven for AFFF.

The following diverse systems have been considered:

1) Friction-reducing additives to increase the flow of water in the deluge system,

2) Gelling agents,

3) Slurries containing flame retardants such as ammonium sulfate, diammonium phosphate and ammonium phosphate, and

4) High expansion foam.

7.2.1 Friction Reducing Agents

Friction reducing additives will increase water flow but the presence of such substances would not bring any improvement over ordinary water, which is ineffective in extinguishing JP-4 fires. The increased flow might, however, aid in protecting the hangar itself. The additive* concentrations required for demonstrable decreases in friction loss in pipes are typically less than 50 ppm by weight.

7.2.2 Gelling Agents

Gelling agents have had a protracted history at FMRC. They were tested primarily for their ability to suppress Class A fuels. There are many failure modes associated with injection of such additives into sprinkler deluge systems, not the least of which is the need to have very narrow tolerances on the proportioning rate (a rate of injection which is too low leads to a thin, watery solution which is essentially no better than ordinary water; if the rate is too high, excessively viscous solutions result, bringing into the picture a number of serious disadvantages). It is suspected that an increase in plume penetration would result from the use of gelling agents, with a corresponding loss in cooling, relative to water, of hangar overheads. The net result would be no better than plain water for this application. It is believed that gelling agents would be less effective and economical compared with conventional foams in protecting aircraft and hangars from fuel spill fires. Therefore, a discussion of the potential pollution hazards of such agents is academic.

*poly(ethylene oxide)

7.2.3 Slurries

Slurries have the same problems associated with them as do the gelling agents. They are ordinarily used effectively only in forest fire applications.

7.2.4 High Expansion Foam

High expansion foams (expansion ratios of 100:1 to 1000:1) can be effective on both Class A and Class B fires. In fact, their use is discussed by National Fire Protection Association Code No. 409-Aircraft Hangars. The pollution potential of high expansion foams for hangar protection, when compared to AFFF, appears to be lower. This conclusion is based on the facts that:

1) Significantly less foam solution per sq ft of floor space would be required with high expansion foam;

2) Its relative lack of fluidity would tend to keep it more localized;

3) High expansion foam concentrate is used at 1.5 vol percent, whereas AFFF is employed at either 3 or 6 percent.

4) High expansion foams are chemically similar to detergents and are normally biodegradable.

Nevertheless, the important counterbalancing deficiencies in application peculiar to high expansion foam systems discussed in Section 6.3, and the fact that the surfactants can cause a discernible foam on water in concentrations as low as a few parts per million, present serious drawbacks to the desirability of such systems for hangar protection.

7.3 BIODEGRADABILITY: AFFF VERSUS PROTEIN FOAM

A major concern recently over AFFF foams has been the effect of the agent upon the environment and aquatic life following discharge. These agents contain saturated fluorocarbons which are largely resistant to biodegradation. Conversely, the less effective protein-based foams have largely been assumed to be non-polluting, because of their "natural" organic base. Review of available literature indicates, however, that both families of agents present inherent environmental problems and that effluents containing either should be processed in some form of sewage treatment facility or diluted prior to discharge into a stream.

In September 1967, the Regional Environmental Health Laboratory (AFLC) at Kelly Air Force Base evaluated protein foam and determined that a biological treatment of foam effluent would be required at Chanute AFB fire fighting school to alleviate reduction of the dissolved oxygen content of a stream.[15] This analysis also indicated that protein foam exhibited relatively low toxicity to microbiological organisms. In 1971, the same organization evaluated 3M Company's "Light Water" Brand AFFF, FC-199.[16] This evaluation indicated that the AFFF materials had both higher Biological Oxygen Demand for five days[10] (BOD_5) and Chemical Oxygen Demand (COD) values, and exhibited greater microbiological toxicity. In fish toxicity tests, this study indicated that fathead minnows could live in a simulated effluent stream containing 250 ppm (v/v) AFFF without fatality for up to eight days, although the 96-hr and 24-hr LC_{50} values were 398 and 650 ppm (v/v) respectively. They concluded that the AFFF tested could be successfully treated in normal sewage treatment facilities and that, if discharged to streams, the discharge should not contain more than 20 ppm AFFF.

Both of the Kelly AFB reports concerned discharge of agent at the fire school at Chanute AFB. At the school, large quantities of foam are used on a continuous basis (up to 2000 gal/per week).[15] In hangar protection, foam discharges are usually intermittent - generally during acceptance and periodic maintenance testing or from an accidental system discharge. The conclusions requiring treatment facilities reached for the Chanute fire school are difficult to justify for a hangar system for which discharges are infrequent (although if an airport or base treatment facility is available, either type of foam can be processed satisfactorily). In analyzing the ecological effect of a hangar foam system, short term exposures should be of primary interest.

When American Airlines proposed installing a foam system in their hangar at Kennedy International Airport, the Port Authority of New York and New Jersey contracted with an independent laboratory to contrast the relative ecological effects of AFFF ("Light Water" FC-199) and protein foam ("Mearl Foam").[17] This report confirmed that the AFFF had higher BOD_5 and COD

values than protein foam, and greater toxicity to fresh water fish (notropis) at low concentrations (less than 2000 ppm). At higher concentrations, however, AFFF and protein foam exhibited essentially equal toxicity. The decision to use AFFF was based on the low number of discharges expected and the fairly negligible differences between protein and AFFF in ecological effect. Part of the consideration was based on the fact that less AFFF would be discharged than protein foam, if 3 percent formulations of both types were used.

Newer formulations of AFFF have been marketed since the above studies were made, including those used in the tests described in this report. BOD_5 and COD values are somewhat higher than FC-199. For example, the BOD_5 and COD values for FC-200 are 50,000 and 720,000 mg/l respectively, while for FC-203, the values are 300,000 and 870,000 mg/l respectively*. Toxicity and microbial inhibition for both agents were reported to be similar to FC-199.

*Personal communication from 3M Company Jan. 22, 1974
Personal communication from 3M Company May 15, 1974.

SECTION VIII
FLOOR DRAINAGE SYSTEMS

8.1 GENERAL

Provision of properly designed and well-maintained drainage systems is an important fire protection criteria in hangars or wherever flammable liquids are handled or stored. NFPA No. 409-Aircraft Hangars, 1973 contains specific design recommendations on drainage systems including the following:

1) The location and spacing of drainage trenches and point-type drains;

2) The slope of the floors to drains;

3) Criteria for the design of drainage piping and special equipment installed in the drainage system such as traps, separators and discharge locations.

Until recently, most hangars were provided with point-type drains spaced a maximum of 40 ft on center. They were located at the bottom of depressions in floors having slopes ranging from 1/4-3/4 percent. Trench drains were usually located only along the doors of the hangar to prevent fuel from flowing out onto the apron where it could expose parked aircraft. In time, there was dissatisfaction with point drainage for two reasons:

1) The drains were susceptible to blockage from parts dropped down the drain or from equipment or debris being located over the drain cover;

2) The "dimpled" floor pattern caused by placing the drains in depressions interfered with aircraft engineering operations. Several airline hangars constructed during the past two decades were designed with flat floors to minimize such interference.

Trench drains largely replaced point drains in hangars constructed in the late 1960's and early 1970's. Trench drains not only minimized the chances of blockage from parts and debris collecting in drainage piping; they also served as fuel spill cutoffs and allowed the use of more gradually sloped floors instead of intermittent depressions in the floor.

8.2 TYPICAL DRAINAGE DESIGNS

Typically, drainage systems are designed to minimize the spread of fuel from one aircraft parking position to another. In hangars, where aircraft are brought straight into the hangar (either nose first or tail first), the drainage systems run parallel to the fuselage. Trenches are located just beyond the outboard engine of the aircraft with the floor sloping from beneath the fuselage toward the trench. The floor also slopes from the wall or adjacent aircraft parking positions to the trench. Specialized trench locations must be provided if the hangar geometry is such that parallel trenches are not feasible or if an existing hangar is modified or extended for servicing larger aircraft. As an example of the former, in a circular or semi-circular type hangar, trenches may run radially from the core section toward the door. In the latter case, trenches may extend perpendicular to the fuselage of the aircraft. In such installations, if the area beneath the aircraft wing and wing center section can be isolated within a common drainage area, it may simplify the design of a supplementary foam extinguishing system for that area.

The provision of sloped floors to facilitate the flow of fuel and fire protection water discharge to the drains is of paramount importance in drainage system design. A nominal slope of 1 percent is normally adequate. It is permissible to design with lesser slopes if the hangar is protected by foam-water sprinkler systems and/or supplementary systems (see NFPA No. 409-Aircraft Hangars, 1973). The required slope may also be reduced if the floor is sufficiently smooth to reduce the friction of the fuel and water flowing to the drains. With rough surfaced floors, however, resistance to flow can only be overcome by provision of sufficient slope.

The effect of sloped floors on aircraft engineering operations has varied from operator to operator in the airline industry. Continental Airlines provided floor slopes of up to 1 percent for their hangars at Los Angeles International Airport. Similarly, Eastern Airlines used a pitch of .8 percent and smooth floors for their new overhaul base in Miami. Aircraft engineering problems caused by sloped floors can be apparently

overcome by proper selection of maintenance equipment such as jacks, work stands, etc. Alternatively, flat spots can be provided on the floor for jack positions or where other equipment requiring stability would be used, while adjacent floor areas slope toward the drains.

SECTION IX
DRAFT CURTAINS

9.1 GENERAL

Traditionally, draft curtains have always played a part in the design of hangar fire protection systems. They were designed to retard heat flow across the ceiling developed during a fuel spill fire, thus preventing operation of remote deluge systems. However, it was shown that draft curtains only slightly reduced the flow velocity of hot gases across the hangar ceiling.[18] Fire gases within a draft-curtained area were expected to be cooled somewhat by the sprinkler discharge. However, while some cooling may occur, gas temperatures are not likely to be reduced sufficiently to prevent operation of adjacent rate-of-rise or rate-compensated detection systems. Thus, sprinkler discharge and not the draft curtains was the major factor depended upon to reduce the operation of remote systems. Because draft curtains provided such limited benefits, NFPA No. 409 was revised in 1973 so that the provisions for draft curtains became advisory and not mandatory.

9.2 POTENTIAL APPLICATIONS OF DRAFT CURTAINS

The feasibility of using a closed-head AFFF sprinkler system for hangar occupancy, described in Section III in this report, reintroduces questions regarding the merit of draft curtains. Unlike rate-of-rise systems, the standard sprinkler link is not rate dependent, but rather depends on the temperature of the fusible link. Thus, since the draft curtain serves as a temporary heat dam, hot fire gases could conceivably be cooled below the temperature rating for the installed sprinkler. The exact rules regarding the installation of draft curtains would require further research, however, in order to determine their optimum depth and spacing, as well as the temperature rating of the sprinklers. Consideration has to be given to the development of automatic curtain closure hardware for areas where necessary hangar utility equipment such as mains, crane rails, etc., pass through the draft curtain.

SECTION X

CONCLUSIONS

The results of the study discussed in this report indicate that:

1. FC-203 is an extremely effective deluge system agent when applied at design densities of 0.16 gpm/ft^2 but dramatically loses effectiveness when applied at a rate of 0.125 gpm/ft^2.
2. No significant differences in fire suppression effectiveness exist between FC-203 and FC-200 at overhead densities of .125 gpm/ft^2 or at 0.1 gpm/ft^2 discharge from a monitor nozzle.
3. At realistic densities of 0.16 gpm/ft^2, 90-percent control times will range between 1 1/2 and 2 min with AFFF deluge systems under optimum conditions, a performance easily capable of adequate hangar protection.
4. At an application rate of 0.1 gpm/ft^2 an oscillating monitor nozzle is capable of achieving 90-percent fire control in 30 to 45 sec under optimum conditions, a performance capable of aircraft protection. It should be cautioned, however, that this is not to imply that monitor nozzles be installed without overhead protection. Experience has shown that obstructions to the horizontal flow of foam from a monitor or mechanical/electrical failure are very real possibilities. Such eventualities without overhead protection could easily result in loss of the hangar in addition to the aircraft.
5. The potential for large reduction in water demand with no sacrifice to fire fighting effectiveness exists with closed head AFFF sprinkler systems in hangars, as contrasted with AFFF deluge systems.
6. The time required to achieve 90-percent fire control with AFFF was two to four times longer than the time required to provide AFFF coverage over 90-percent of a non-fire fuel surface of the same area. This difference in time is due to heat and products of combustion.

7. Direct plume penetration into the center of flammable liquid hydrocarbon fires by deluge-system-generated foam particles is predicted to occur only with small fires (less than 10^2 ft^2). Deluge systems attack larger spill fires (e.g. 10^3 ft^2 or more) in two ways: 1) impingement of particles onto the fuel surface within the fire perimeter but to distances of no more than ~50 percent of the radius (in the radial direction toward the center); and 2) foam blanket flow from the fire perimeter inward.
8. The only supplementary low-level foam system other than oscillating monitor nozzles considered practical at this time is high expansion foam.
9. At present, the only agents which can be injected into suppression systems and achieve fire fighting effectiveness on flammable liquid hydrocarbon spill fires even closely comparable to AFFF are other types of low expansion foams.
10. The real operational problems with respect to pollution are basically the same for AFFF as for protein foams.
11. If designed properly for a given hangar with respect to occupying aircraft and their parking positions, drainage systems can provide a high degree of fire preventive measure in addition to reducing suppression times and limiting fire area without significantly hindering maintenance operations.
12. It does not appear that draft curtains in large aircraft hangars can provide any real benefit, except possibly in the eventuality of closed-head AFFF sprinkler systems.

SECTION XI
RECOMMENDATIONS

Additional studies should be initiated to investigate further closed-head sprinkler systems for hangar application by conducting tests designed to evaluate the variables of design density and fusible link temperature rating, with and without draft curtains and simulated wing obstructions.

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